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**Objective measurements of skull vibration  
during bone conduction audiometry**

**INAUGURAL-DISSERTATION**

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presented by  
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## 1. Abstract

**Background:** Two different pathways of sound transmission to the inner ear are differentiated; air conduction (AC) and bone conduction (BC). The transmission pathway of AC, which is physiological for human hearing, implies the transmission of sound to the cochlea via the ear canal, eardrum, and middle-ear ossicles, while BC bypasses the Pinna, the external auditory canal and the middle ear. The transmission pathway by BC has not been fully understood and many aspects still remain questionable.

The aim of this study is to characterize two ways of direct transmission of vibrations to the inner ear by measuring hearing thresholds and vibrations of the skull. The bone-vibrator, which is usually used to measure the BC hearing thresholds in contact with the mastoid, can also be used to simulate other contents of skull, such as the eye.

**Methods:** Ten adults (age range of 25-40) with normal hearing and five patients (age range of 21-31) with single sided profound deafness (SSD) were included in this study. The AC audiometry by pure tones was measured using insert earphones and the BC audiometry was measured by stimulating four different locations of the skull; the forehead, the temporal region, the mastoid, and the ipsilateral eyeball with two different contact pressure magnitudes of 2N and of 5N. The vibrations of the skull bones induced by air and bone conduction stimuli were measured by an accelerometer positioned between an upper and lower front incisor tooth.

**Results:** The BC hearing thresholds by stimulating the temporal region and the mastoid were the lowest in both of normal hearing and SSD subjects and the values by both stimulations were similar. Thresholds were significantly higher for stimulations on the forehead and the eye ( $p<0.05$ ). The difference between the thresholds by stimulation at the mastoid or temporal region and at the eye was more pronounced in SSD subjects ( $p<0.01$ ). The averaged BC thresholds of normal subjects by stimulation on the contralateral temporal region were significantly lower than the averaged BC thresholds of SSD subjects only at the frequency of 0.25 kHz ( $p<0.01$ ). The BC thresholds by stimulation on the contralateral mastoid of the normal hearing subjects were significantly lower in 5 N headband than in 2 N headband at the whole frequency range ( $p<0.05$ ). The BC thresholds by stimulation on the ipsilateral mastoid of the normal hearing subjects showed significant differences between the contact pressure forces of 5 N and 2 N at the frequencies of 1, 2, and 3 kHz ( $p<0.5$ ). The stimulation on the contralateral mastoid with the 5 N headband resulted in a significantly lower BC threshold than the stimulation with

the 2 N headband at the entire frequency range ( $p < 0.05$ ). In SSD subjects, the stimulation on the ipsilateral mastoid side with the 5 N headband had a significantly lower BC thresholds than stimulation with the 2 N headband at all frequencies except for 0.5 and 4 kHz ( $p < 0.05$ ).

The BC thresholds in normal hearing subjects were significantly lower with the ipsilateral temporal stimulation than with a corresponding contralateral stimulation for the all frequencies except for 0.5 and 1 kHz ( $p < 0.01$ ). For the SSD subjects, the BC thresholds with the ipsilateral temporal stimulation were significantly lower at 2, 3 and 4 kHz than those with the corresponding contralateral stimulation.

Skull vibrations in the normal hearing subjects showed similar behaviors at low frequencies up to 2 kHz for all stimulations except for stimulation on the eye, where vibrations were smaller. In contrast, skull vibrations measured from stimulation at the eye were increasing with higher frequencies. Under 2 kHz skull vibrations at eye were significantly smaller than those from stimulation of the mastoid, but above 2 kHz, they were significantly bigger ( $p < 0.05$ ). Skull vibrations between stimulation at the ipsilateral mastoid and forehead were significantly different at 0.25, 3 and 4 kHz ( $p < 0.05$ ). The subjects with SSD showed similar patterns.

**Conclusion:** The patterns of BC hearing thresholds were similar in normal subjects and subjects with SSD. Hearing thresholds in all subjects were significantly better for mastoid and temple stimulation compared to eye stimulation. One reason for that may be the different pressures applied. Skull vibrations as measured at teeth did not match the same pattern as the hearing thresholds. Eye stimulation induced low vibrations below 2 kHz, but high vibrations above 2 kHz. This finding demonstrates special acoustic properties of the living organism, the distance from stimulation might also contribute. Skull-bone vibrations decreased with increasing frequency for mastoid and temple stimulation. Stimulation of soft tissue, presumably including skull contents, seems to induce high frequency skull vibrations. That might be involved with the distance from the front teeth. The transcranial attenuation of vibration should be considered especially in high frequencies.

## **2. Introduction**

Two different pathways of sound transmission to the inner ear are generally distinguished in clinical audiology. The first, air conduction (AC), is the physiological and primary pathway transmitting airborne sound to the cochlea via ear canal, eardrum, and the middle ear ossicles. The second way is bone conduction transmitting vibrations of bone and other tissues to the inner ear. The transmission pathways of bone conduction are not understood completely [1]. It is likely that vibrations are transmitted partially through true bone conduction and partially through vibration of soft tissue including the skull contents [2]. It is difficult to differentiate the contributions of these two vibration pathways to conductive hearing.

The BC stimuli are routinely used in order to differentiate between a conductive and a sensori-neural hearing loss. Skull vibrations induced by the bone vibrator are transmitted through the skull and its contents exciting the inner ear. The major pathway is traditionally thought to be osseous so that the bone vibrations induced by the vibrator at the point of application on the skull are transmitted as transverse waves along the skull bones to the inner ear [3].

However, Sohmer et al. [2] found the fact that stimulation of the cochlea can also be obtained with placements of the bone vibrator on the eye with only moderately higher thresholds. Because the eye can be considered as fluid and tissue with communications to the skull contents but not to the bone, this kind of stimulation points to additional pathways of sound transmission besides the bone vibration.

The vibration properties of the skull bones and contents have been examined only scarcely in living human. Most of the study on vibrations of the human skull has been done in dry skulls gel-filled or empty[12-15]. It is not clear if measurements in these conditions apply to living human with closed fluid and soft tissue skull contents under some pressure.

### **2.1 Bone vibration**

A bone-vibrator is usually brought into contact with the mastoid for measuring BC thresholds in clinical audiometry. Vibrations from the transducer travel directly to the skull bone. An important consideration in the use of bone conducted stimulations is placement

of the bone vibrator. The placement of the vibrator against the upper front teeth instead of the usual place on the mastoid process gave 7 dB lower thresholds and approximately 10 dB lower than a placement on the center of the forehead [4]. In addition, small variations of vibrator placements can lead to marked changes of the effective stimulation. The signal levels measured in the external auditory meatus were significantly changed when varying the position of the bone vibrator over the forehead [5]. An effective contribution to the transmission of vibratory energy to the inner ear is through the non-osseous transmission mechanisms, particularly at lower frequencies [6].

There are three widely accepted theories of bone conduction hearing that attempt to clarify the relative contributions of these mechanisms in the normal subject and those with conductive hearing loss; first compressional BC, second inertial BC, and third osseotympanic BC [7]. The compressional BC describes the alternating compression and expansion of the otic capsule in response to skull vibration. The inertial BC describes the contribution of the middle ear structures to BC hearing. The ossicles are loosely attached to the skull and the otic capsule. Ossicular vibration is a consequence of skull vibration caused by different resonance properties of the two; they have different amplitudes and phases [8]. Osseotympanic BC describes sound energy transmitted to the external ear canal via the skull and para-auditory structures (jaw, soft tissues) to the tympanic membrane [9, 10].

Traditionally, BC threshold measurements have been conducted with the transducer applied on the mastoid portion of the ipsilateral temporal bone [11]. However, many researchers have argued that the forehead is a better location for BC transducer because it is less sensitive to variations in stimulation position. They have performed vibration experiments in the audiometric frequency range (up to 10 kHz) on human heads, cadaver heads and animals, as well as human dry skull preparations, both gel-filled and empty [12-15]. Bone conduction pathway involving skull vibration transmission entirely along bone to the temporal bone requires further consideration.

Thresholds on the teeth were better than those on the forehead and there was no difference between the thresholds measured following stimulation of the upper and lower teeth. There is almost a direct coupling between the skull bone and the teeth, without the skin and soft tissue in the transmission pathway [16]. These studies have found a variety of resonances and anti-resonances in the audiometric frequencies.

When patients use conventional hearing aids with conventional closed fitting, a common complaint is that their own voices sound unnatural, because the otoplasty occludes more or less the ear canal. This phenomenon is partly explained by an increased sensitivity to bone-conducted sound when the ear canal is occluded. Sound pressure in the external ear canal due to BC stimuli can be elevated at frequencies below 2 kHz when the opening of the external ear canal is occluded; this is called the occlusion effect. The occlusion effect was obtained in two clinical audiometric settings: with supra-aural earphones (TDH39), and insert earphones (CIR22). Both transducers produced occlusion effects, but insert earphones produced a greater effect than supra-aural earphones at the low frequencies [17]. The threshold improvement caused by the occluding device is usually on the order of approximately 10 to 20 dB at 250 Hz and 500 Hz, with little or no improvement at frequencies above 1000 Hz. It is significant to note that there is a reduced or absent occlusion effect (as measured by BC thresholds) in cases of conductive hearing loss. When the canal is occluded, the low-frequency energy is “trapped” and transmitted into the inner ear.

## **2.2 Masking**

Masking of the non-tested ear is necessary in bone vibration audiometry for one-sided measurement of normal subject and conductive hearing loss patient. Even though some amount of attenuation from one ear to the other exists (the so-called transcranial attenuation) the amount of attenuation is small and valid thresholds can be measured only with masking. The transcranial attenuation for bone conduction was frequency dependent, with values ranging from 0-20dB [18, 19].

Masking of the non test ear is therefore a requirement to achieve testing of one ear, regardless of the stimulation site used. However, masking itself can influence the BC thresholds. Masking of the non-tested ear is achieved by using "effective masking" (*i.e.* 40 dB greater than the non-tested-ear threshold) and by reaching a plateau, during which the test ear hears the pure tone at the same level. Effective masking is used primarily to save time. Masking without a plateau can lead to either undermasking or overmasking. Overmasking occurs when the masker in the non-test ear crosses to the test ear. Overmasked thresholds get too high because of unintentional masking of the test ear.



Undermasked thresholds get to low because of bilateral summation. It can be difficult to find the right level of masking in certain clinical settings.

Using masking can influence the thresholds obtained. An earphone in the ear may introduce an occlusion effect that improves the low-frequency BC thresholds up to 20dB [11, 20]. If an insert earphone is used to provide the masking stimulus and the insert earphone is positioned down to the bony part of the ear canal, the occlusion effect is minimized.

### **2.3 Subjects with single sided deafness**

A profound single sided hearing loss imposes well-recognized communication difficulties. Single sided deafness (SSD) is the term given to significant sensorineural hearing loss or total hearing loss in one ear and more or less normal hearing in the other.

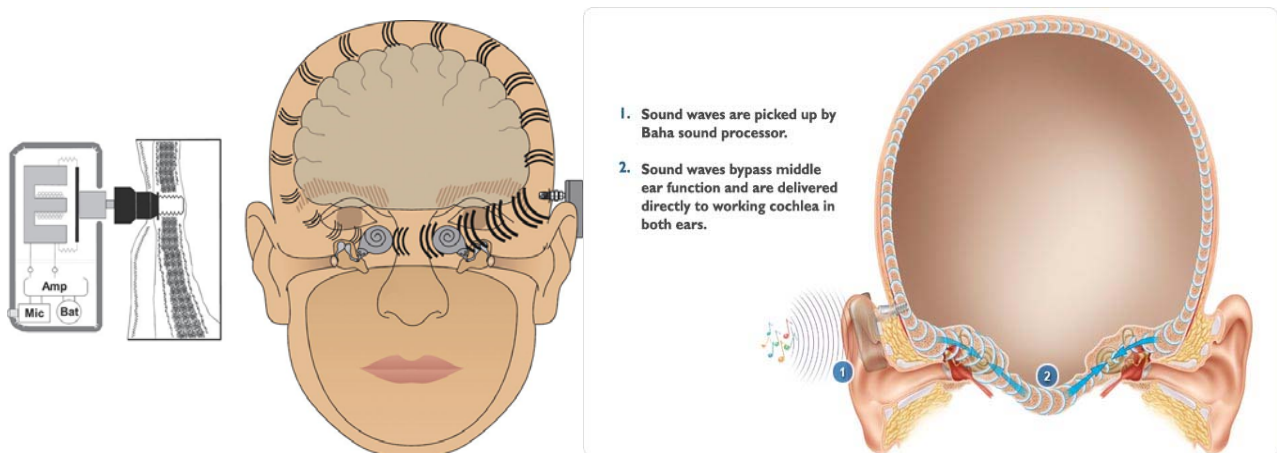
Adults with unilateral profound deafness can experience difficulties in verbal communication despite the presence of normal hearing in one ear [21]. The greatest difficulties for monaural listeners occur when the sound source of interest is either positioned on the side of impairment or when reverberations or interfering noise corrupt the cues for sound localization [22]. Unilaterally hearing impaired persons, who may experience substantial communication problems in situations of high acoustic demands, would in theory benefit from contralateral routing of signals [21].

Unilateral hearing loss may modify information processing in the central auditory system cause reorganization of the central auditory pathway. In patients with unilateral inner ear deafness, the presence of only one functioning cochlea precludes the use of interaural time and intensity differences essential for directional hearing. Patients with only one functioning cochlea lack the cues essential for directional hearing and intensity differences [22]. Interaural time and intensity differences occur when stimulation of one cochlea closer to the stimulation point is at a higher level than of the other cochlea [25, 26].

Single sided deaf subjects are ideal for studies on the transcranial attenuation of bone-conducted sound. Such studies revealed interestingly large peaks of attenuation in the sound transmission to the cochlea nearest the excitation point for some frequencies [23].

The bone-anchored hearing aid (BAHA) is a highly effective hearing aid in patients with aural atresia or chronic otitis media or chronic otitis externa [24]. Auditory rehabilitation with the BAHA system relies on BC auditory stimulation evoked by vibration of the cochlea fluids. It is well recognized that bone conduction of sound may be transmitted transcranially by virtue of the fact that the otic capsule is ensconced in the rigid basicranium. This form of sound transmission can occur with a vibrational source placed virtually anywhere on the skull [13].

Subjects with conductive and mixed hearing impairment are often fitted with BAHA (Illustration 1). The BAHA makes use of a titanium abutment that has been surgically implanted behind the ear into the bone to form a permanent, secure bond (osseointegration) with the skull. The BAHA then clips onto this abutment, and transmits the sound by bone conduction directly to the bone (percutaneous transmission). This direct contact (as opposed transcutaneous or through the skin) translates into several advantages, including lower power consumption from the hearing aid and lower distortion in the sound produced.



**Illustration 1.** The Bone-Anchored Hearing Aid. The microphone picks up the sound which is amplified and filtered by the amplifier, supplied by a battery, and is converted to vibrations by the transducer. The transducer is connected by a snap or bayonet coupling to the osseointegrated titanium fixture, rigidly anchored in the skull bone. The figure illustrates schematically the transmission paths of bone conduction sound from the BAHA to the cochlea.

Stenfelt et al. [26] observed marked sound lateralization to the contralateral cochlea in the frequencies between 0.5 and 1 kHz resulting from effects of transcranial attenuation from antiresonances. If BAHAs were used in SSD, marked sound lateralization to the contralateral cochlea was observed in the frequencies between 0.5 and 1 kHz resulting from effects of transcranial attenuation from anti-resonances [27]. An increase in attenuation with an increase in frequency, as well as significant resonance effects, was observed. For the audiometric frequency range, bone conduction stimulation of one side of the head results in almost equal stimulation of the other side [28].

In terms of hearing rehabilitation with the BAHA system, these findings by Stenfelt et al. [26] and Brandt [30] indicate that the best transmission to the best working cochlea may be obtained if the skull is excited at the contralateral side. Such is the case with the current strategy of hearing restoration for unilateral deafness with the BAHA system.

## **2.4 Aims of thesis**

It is important to know the difference of transmission level in unilateral profound deafness, when a vibrator is used at different sites and also how the hearing thresholds and skull vibration differ between normal subjects and subjects with single sided deafness.

The first of the aims of this thesis was to measure hearing thresholds at different sites of vibrator placements including soft tissue. The second was to measure at the same time objectively the skull vibration induced at these sites using 5 N and 2 N headbands for bone vibrator. Specific questions included:

Where is the best stimulation side for subjective BC hearing threshold and objective vibration?

Is there a relationship between static pressure and distance in the subjective hearing threshold and the vibration magnitude?

Does stimulation of the eye induce bone vibration as measured at the teeth?

### **3. Subjects and Methods**

#### **3.1 Subjects**

Normal subjects: Ten subjects (25 to 40 yrs, mean = 31 yrs, 8 men and 2 women) in good general health were tested. The subjects reported no difficulty with hearing. AC thresholds were better than 25 dB HL in the pure-tone audiogram.

Subjects with single sided deafness: Five patients with single sided deafness were tested. The ages of the patients were 21 to 31 years (mean = 25 yrs, 4 men and 1 women). Hearing levels for AC between 0.25 and 4 kHz for these patients were better than 25 dB HL in the normal hearing ear and worse than 90 dB HL in the deafness ear.

This study was approved by the Ethic Committee of the Zürich University Hospital.

#### **3.2 Method**

The tests were performed in a sound proof room.

##### **3.2.1 AC Pure-tone threshold:**

Standard pure-tone air conduction thresholds were performed bilaterally in normal subjects and unilaterally in subjects with single sided deafness. AC thresholds were obtained at the frequencies of 0.25, 0.5, 1, 2, 3, 4, and 8 kHz with an audiometer (MADSEN, ORBITER922DH/2) using insert earphones (E.A.R. Auditory Systems, E.A.R. Tone 3A).

##### **3.2.2 BC Pure-tone threshold:**

Bone vibration audiometry was recorded with stimulation at the forehead, at a restricted area of the temporal region used for transcranial ultrasound examinations -the ultrasound window above the zygomatic bone -, and at the mastoid with a static force of 5 N provided by a steel headband and checked with a spring scale (PESOLA, Light Line). In addition, the vibrator was applied at the ipsilateral eye using a headband with a static force of 2 N.

The recommended static force for clinical bone conduction measurements is over 4 N. The IEC and ANSI recommend that the force against the mastoid should be 5.4 N. BC pure-

tone audiometric thresholds were performed at 0.25, 0.5, 1, 2, 3, and 4 kHz using a bone vibrator (Radioear Corp., Radioear B-72) routed from the standard audiometer.

A conventional bracketing method was used to obtain responses using a 5-dB step size, and participants responded by pushing a response button.

When the bone vibrator was placed on the eye, the subject was instructed to close the eyes, and to assure that the bone vibrator did not make contact with the bony rim of the orbit. For comparison, BC thresholds were measured in two subjects at all placements with both a static force of 2 and 5 N with the exception of 5 N at the eye.

Normal subjects: BC thresholds were measured at the side of better AC thresholds. To ensure that bone conducted responses were obtained only from the measured ear, narrow band masking at 60 dB HL was applied to the opposite ear with insert earphones coupled to the ear with foam earplug.

Subjects with single sided deafness: BC thresholds were measured in the same way as in normal subject. To prevent the perception of air-conducted sounds radiating from the bone vibrator, the external auditory canal of both ears were blocked with a foam earplug during measurements of BC thresholds, thereby inducing an occlusion effect.

### **3.2.3 Measurement of vibration (bone-conducted stimuli)**

Vibrations of the skull bones were measured with an accelerometer (Brüel and Kjær, type 4374), which was coupled to the teeth. All subjects had their own natural teeth. Subjects were instructed to bite the plastic housing containing the accelerometer between an upper and lower front incisor tooth with sufficient and constant pressure.

Appropriate breaks were installed. The bone vibrator was applied to the same sites and with the same methods as used in the measurement of BC thresholds, including the ipsilateral eye. Pure tone stimulation was presented at 50 dB HL and vibration was measured during the stimuli at the frequencies of 0.25, 0.5, 1, 2, 3, 4 kHz. In addition, stimuli of 60 and 70 dB HL were applied at 1 and 2 kHz.

For each frequency the output voltage of the charge amplifier ( $V_{rms}$ ) was averaged 100 times and documented. Thereby a reliable signal to noise ratio of typically 10 to 20 dB was

obtained. The recorded signal was then converted to dB for easy comparison (1microV equals 1m/s<sup>2</sup> equals 0dB acceleration amplitude). Stimulus generations and measurements were controlled by National Instruments, Lab VIEW 7.1 software operating on a IBM computer using multi-function DAQ device (National Instruments, PCI 6052E). The signal was visually controlled with an oscilloscope (HAMEG, HM203-7). An adaptor (National Instruments, BNC-2110) was used to the computer (Illustration 2).

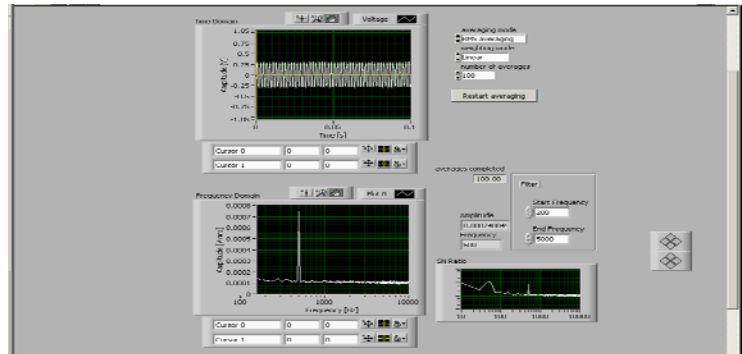
### 3.2.4 Statistical analysis

One-way ANOVA analysis with Turkey test were used to determine significant differences between the stimulation sites in hearing thresholds and skull vibrations. Statistical analyses of the results were carried out using the Stata program. We calculate a one-sided P value of comparison of static force between 5 N and 2 N using Wilcoxon test.

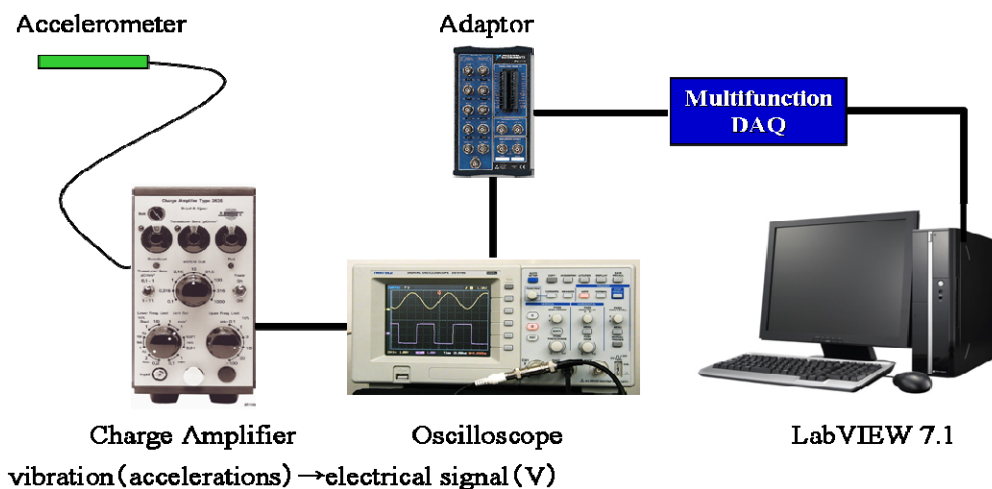
**A**



**B**



**C**



**Illustration 2.** System of vibration measurement. **A** The subject bites the accelerometer between an upper and lower front incisor tooth, **B** the result of frequency 500 Hz and frequency domain, and **C** System of electrical signal from vibration.

**Table 1. Overview of subjects and methods**

		Normal subjects	Subjects with single sided deafness
Age		25-40 (mean=31.8)	21-31(mean=25.4)
Subjects	Man	8	4
	Woman	2	1
AC Frequency		0.25, 0.5, 1, 2, 3, 4, 8 kHz	
Masking		o	X
BC Frequency		0.25, 0.5, 1, 2, 3, 4 kHz	
Insert earphone		o	X
Frequency of Skull vibration		0.25, 0.5, 1, 2, 3, 4 kHz	
Place of stimulation	5 N	Mastoid side, temporal region and forehead side	
	2 N	Eye side	

o= yes

X= no

## **4. Results**

### **4.1 Bone conduction hearing threshold**

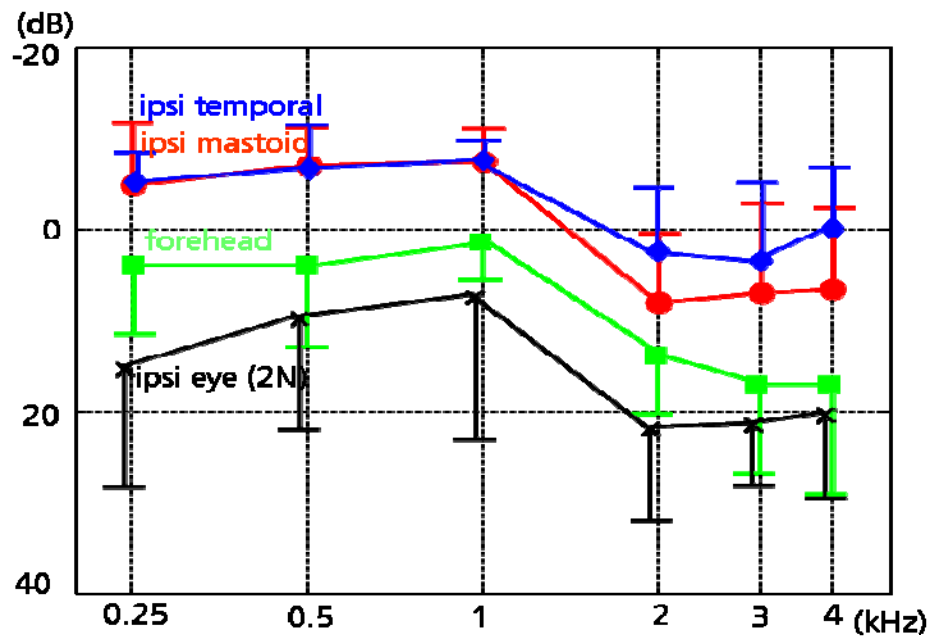
#### **4.1.1 Results of the BC hearing thresholds in several sites**

Ten ears were measured of ten normal hearing subjects. Figure 1 illustrates the mean subjective hearing thresholds when the bone vibrator with a 5 N headband was placed on various sites of the skull. The BC hearing thresholds were similar for stimulation at the mastoid and temporal region. BC thresholds of these regions were lower compared to the stimulation at the forehead and eye. BC thresholds at the forehead were significantly higher than at the temporal region for the entire frequency range ( $p < 0.05$ ).

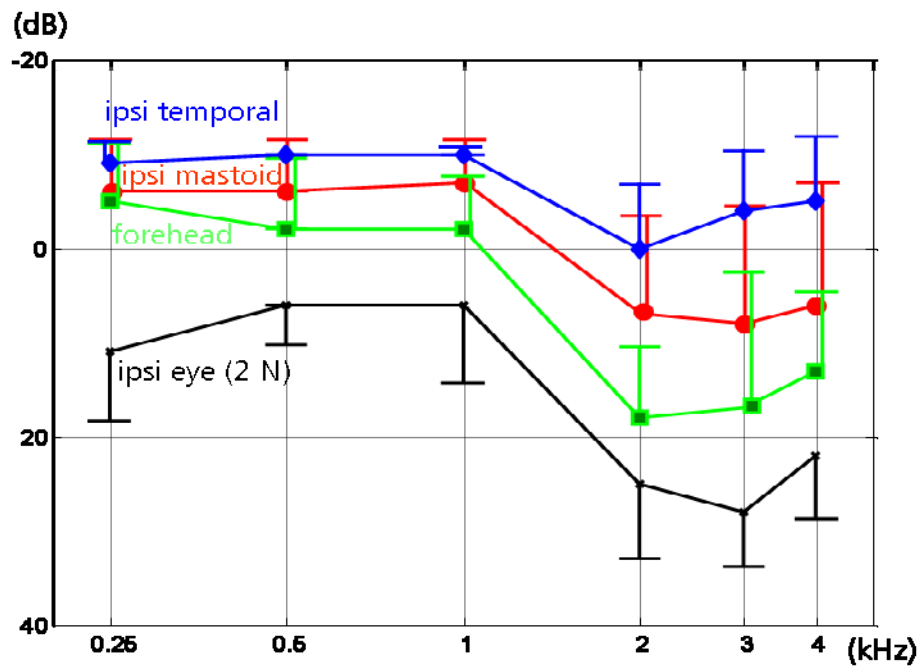
Stimulation at the ipsilateral eye showed the highest thresholds. BC thresholds at the ipsilateral temporal region were highly significantly lower ( $p < 0.001$ ) than at the ipsilateral eye, and they were also significantly lower at the ipsilateral mastoid region ( $p < 0.05$ ). The thresholds on the forehead were significantly higher than those on the ipsilateral mastoid at 0.5 and 3 kHz ( $p < 0.05$ ).

Five ears of subjects with single sided deafness and occlusion of the ear canal were measured. Figure 2 shows the BC hearing thresholds of subjects with single sided deafness. Similar pattern of thresholds as in the normal hearing subjects are evident and stimulation at the eye showed again the highest thresholds. The stimulation at the ipsilateral temporal region showed lower thresholds than at the mastoid, but not significantly. The audiometric BC thresholds obtained with placement on the ipsilateral mastoid and temporal region were significantly lower than those on the ipsilateral eye for the entire frequency range ( $p < 0.01$ ). BC thresholds at the forehead were significantly lower than stimulation at the ipsilateral eye at 0.25 and 1 kHz ( $p < 0.05$ ). BC thresholds compared between stimulation at the forehead and at the ipsilateral temporal region were significantly different at 1, 3, and 4 kHz ( $p < 0.05$ ).





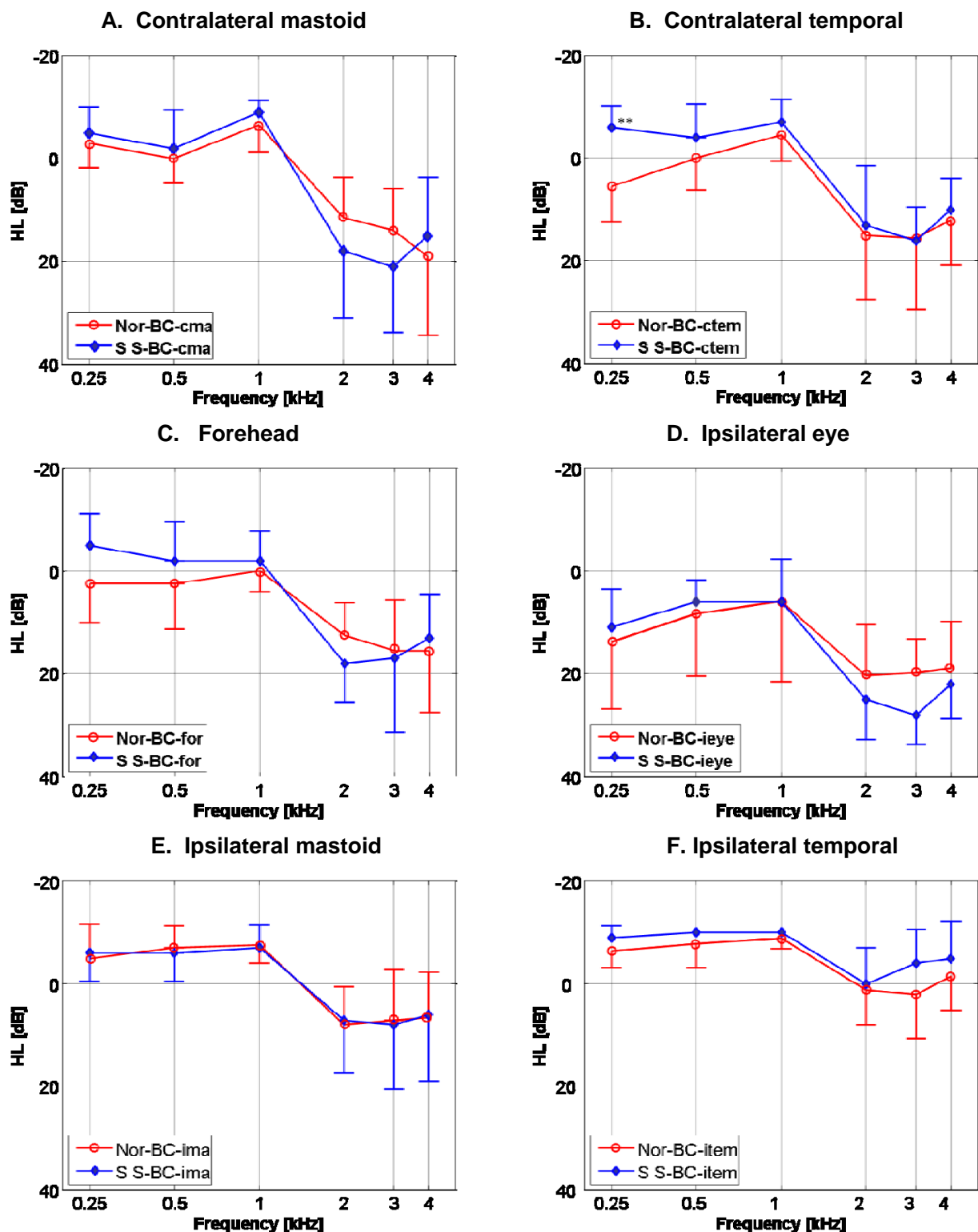
**Fig. 1.** Mean ( $\pm$  standard deviation) BC hearing thresholds of normal hearing subjects ( $n=10$ ). *ipsi* = *ipsilateral*. The BC thresholds for the eye and forehead placements were significantly higher than those for the temporal site ( $p<0.05$ ).



**Fig. 2.** Mean BC hearing thresholds of subjects with single sided deafness ( $n=5$ ). The BC thresholds obtained with placement on the ipsilateral mastoid and temporal region were significantly lower than those with an ipsilateral eye placement for the entire frequency range ( $p<0.01$ ).

#### **4.1.2 Comparison of BC thresholds between normal subjects and subjects with single sided deafness**

Figure 3 shows the results of BC thresholds in normal subjects and subjects with single sided deafness in all tested sites (A - F). BC thresholds were similar at placement on the contralateral and ipsilateral mastoid, and at the ipsilateral temporal region. Averaged BC thresholds of normal subjects on the contralateral temporal region at 0.25 kHz were significantly higher than the averaged BC thresholds of subjects with single sided deafness ( $p < 0.01$ ). BC thresholds of subjects with single sided deafness at the other sites were not significantly difference than normal subjects.



**Fig. 3.** Comparison of mean BC thresholds between normal subjects ( $n=10$ , Nor-BC, red) and subjects with single sided deafness ( $n=5$ , SS-BC, blue). **A** Contralateral mastoid, **B** Contralateral temporal, **C** Forehead, **D** Ipsilateral eye, **E** Ipsilateral mastoid, and **F** Ipsilateral temporal. Thresholds of normal subjects and subjects with single sided deafness were similar except at 0.25 kHz at the contralateral temporal region.

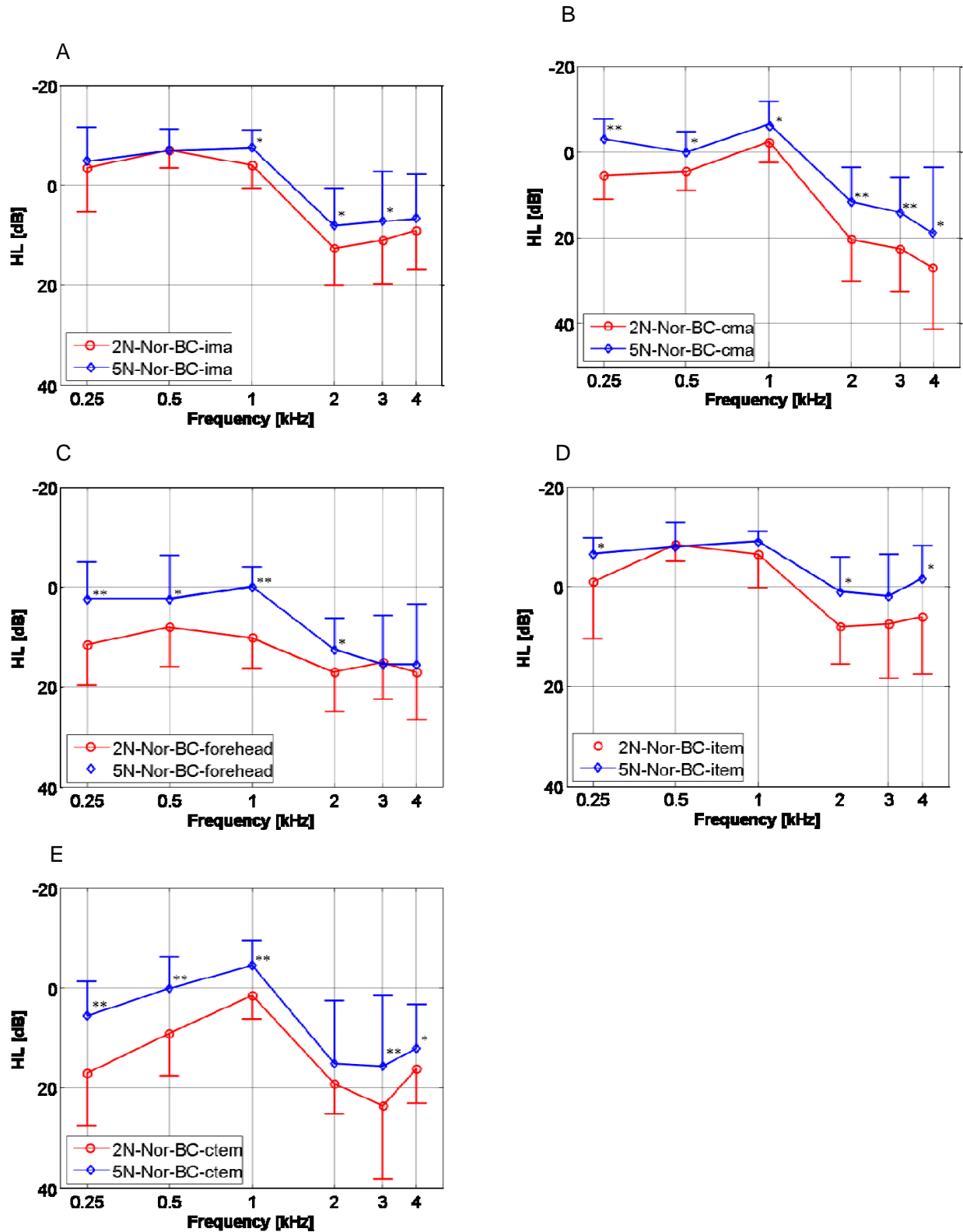
### **4.1.3 Results of BC hearing thresholds between 5 N and 2 N headband in normal subjects and subjects with single sided deafness**

#### **4.1.3.1 Results of BC hearing thresholds in normal subjects**

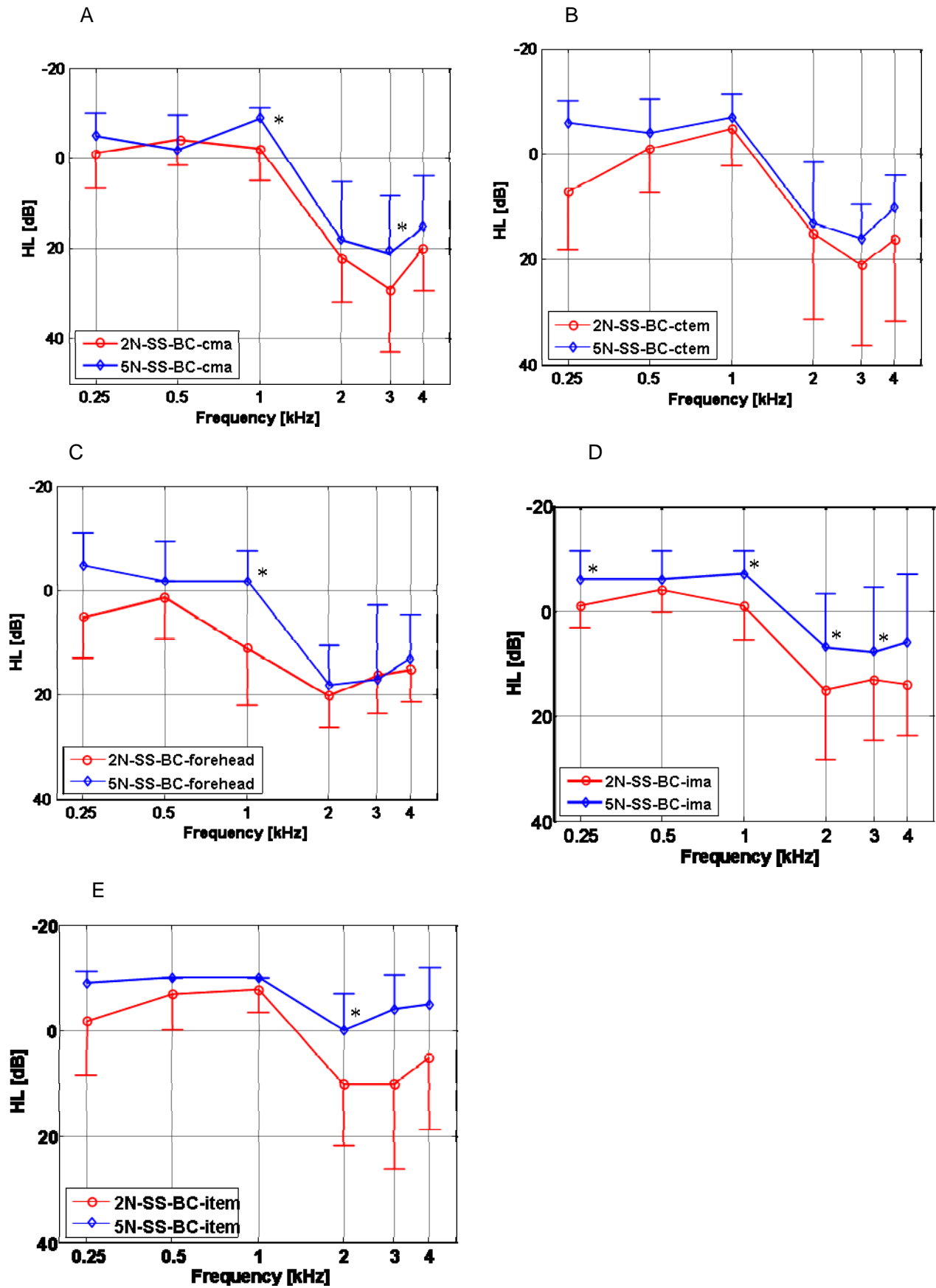
Figure 4 showed the results of BC thresholds compared between a 5 N and a 2 N headband in normal subjects. The results of BC thresholds between 5 N and 2 N headband were significantly different at 1, 2 and 3 kHz of the ipsilateral mastoid site ( $p < 0.05$ , A). BC thresholds of the contralateral mastoid site with a 5 N headband were significantly lower than with a 2 N headband at the entire frequency range ( $p < 0.05$ , B). At the forehead, the 5 N headband lead to significantly better thresholds than the stimulation with a 2 N headband at the frequencies of 0.25, 0.5, 1 and 2 kHz ( $p < 0.05$ , C), but not at 3 and 4 kHz. The BC thresholds of the ipsilateral temporal region with a 5 N headband were also significantly lower than stimulation with the 2 N headband at 0.25, 2 and 4 kHz ( $p < 0.05$ , D). BC thresholds of the contralateral temporal region with a 5 N headband were also significantly different at all frequencies except at 2 kHz ( $p < 0.05$ , E) than the stimulation with a 2 N headband.

#### **4.1.3.2 Results of BC hearing thresholds in subjects with single sided deafness**

Figure 5 shows the results of BC thresholds of subjects with single sided deafness obtained with 5 N and 2 N headbands. BC thresholds at the contralateral temporal region were not significantly different for the 5 N and 2 N headband, but BC thresholds at the contralateral mastoid site were significantly lower with the 5 N than with the 2 N headband at 1 and 3 kHz ( $p < 0.05$ , A and B). BC thresholds at the ipsilateral mastoid with the 5 N headband were significantly lower than stimulation with the 2 N headband at the entire frequency range except 0.5 and 4 kHz ( $p < 0.05$ , D). BC thresholds at the forehead and the ipsilateral temporal region with the 5 N headband were significantly lower than stimulation from the 2 N headband at one frequency only, for the forehead at 1 kHz, for the temporal region at 2 kHz ( $p < 0.05$ , C and E).



**Fig. 4.** Comparison mean BC thresholds of 5 N (blue) and 2 N (red) headband of normal hearing subjects (n=10) at different sites. **A** Ipsilateral mastoid, **B** Contralateral mastoid, **C** Forehead, **D** Ipsilateral temporal, and **E** Contralateral temporal. Significance of differences is indicated by \* (p<0.05) or \*\* (p<0.01).



**Fig. 5.** Mean BC thresholds of 5 N (blue) and 2 N (red) headband of subjects with single sided deafness (n=5). **A** Contralateral mastoid, **B** Contralateral temporal, **C** Forehead, **D** Ipsilateral mastoid, and **E** Ipsilateral temporal. Significance of differences is indicated by \* ( $p < 0.05$ ).

#### **4.1.4 Results of the BC hearing thresholds for ipsilateral and contralateral side in mastoid and temporal region**

##### **4.1.4.1 BC hearing thresholds with the 5 N headband in normal subjects**

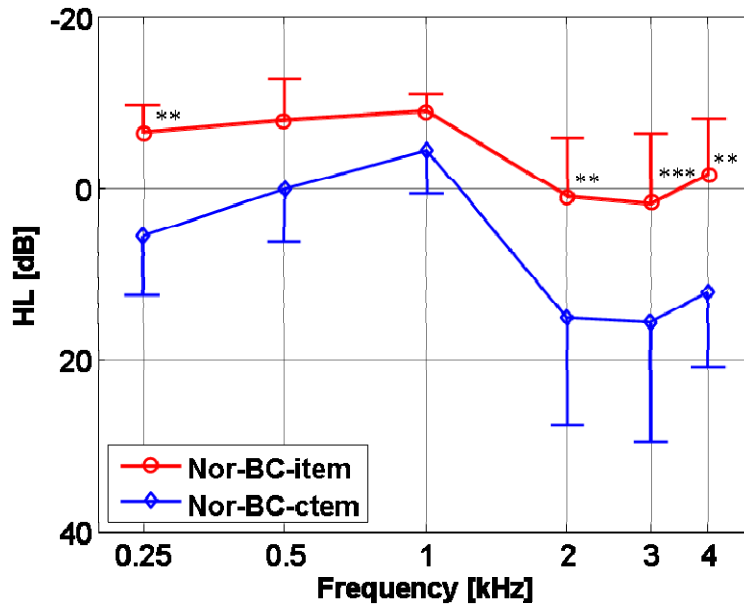
Figure 6 shows the results of BC thresholds of ipsilateral and contralateral temporal regions in normal subjects. BC thresholds obtained with the placement on the ipsilateral temporal region were significantly lower than those from the contralateral temporal region for the entire frequency range ( $p < 0.01$ ) except at 0.5 and 1 kHz.

Figure 7 shows BC thresholds of the ipsilateral and contralateral mastoid in normal subjects. The BC thresholds at the ipsilateral and contralateral mastoid were not significantly different except at 4 kHz ( $p < 0.01$ ).

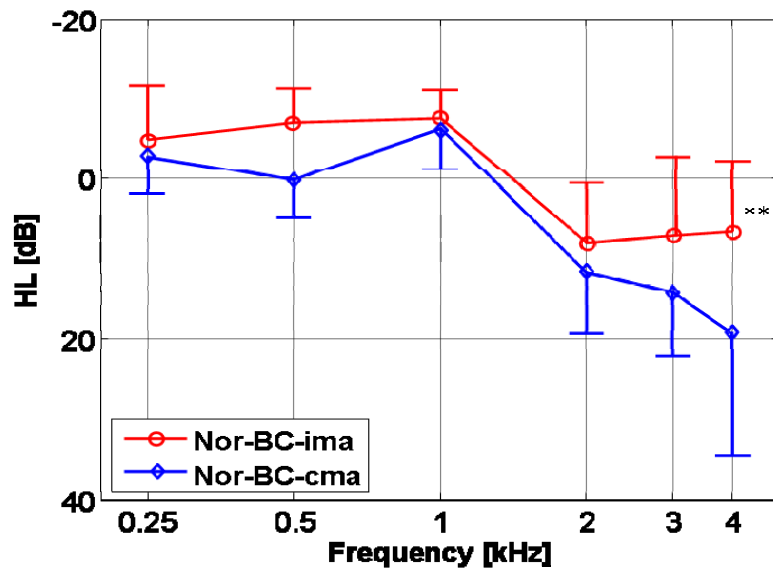
##### **4.1.4.2 BC hearing thresholds with 5 N headband of ipsilateral and contralateral side in subjects with single sided deafness**

BC thresholds were similar for the contralateral and ipsilateral mastoid side, with the exception of the thresholds at 3 kHz. BC thresholds at the 3 kHz of ipsilateral mastoid side was significantly lower than at the contralateral side ( $p < 0.05$ , Fig. 8).

As shown in Fig. 9, even though BC thresholds of the ipsilateral temporal site were lower than those from the contralateral side, the difference reached significance only at the frequencies of 2, 3 and 4 kHz ( $p < 0.05$ ).

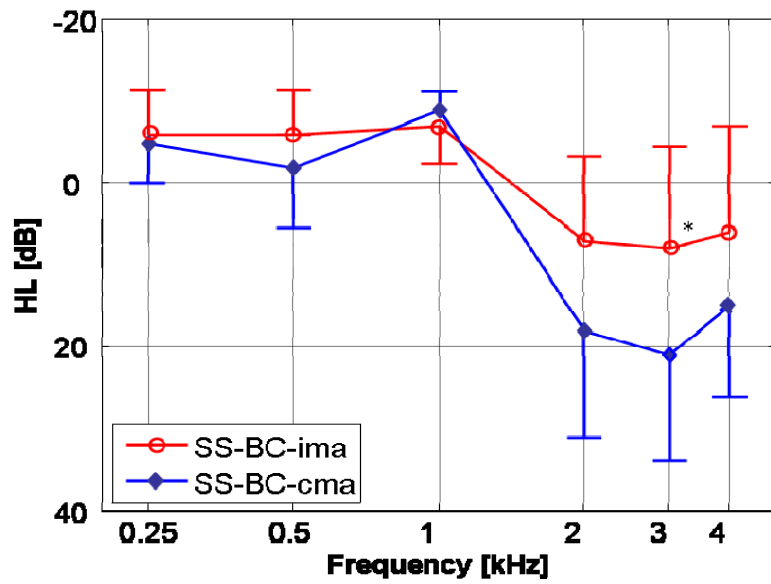


**Fig. 6.** Mean BC thresholds of normal subjects with stimulation at the ipsilateral (red) and contralateral (blue) temporal region. Ipsilateral BC thresholds were significantly lower than contralateral for the entire frequency range except at 0.5 and 1 kHz ( $p < 0.01$ ).

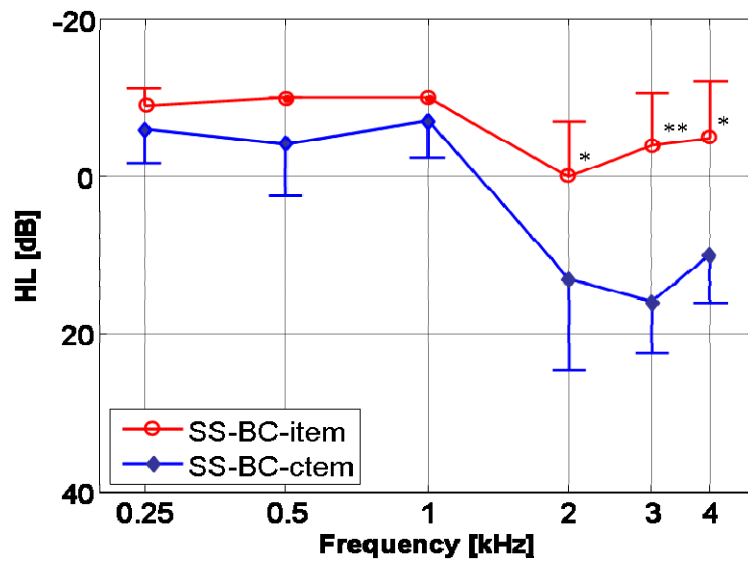


**Fig. 7.** Mean BC thresholds of normal subjects in ipsilateral (red) and contralateral (blue) mastoid sites. The BC thresholds at the ipsilateral mastoid site were not significantly different from the contralateral mastoid site except at 4 kHz ( $p < 0.01$ ).





**Fig. 8.** Mean BC thresholds of subjects with single sided deafness at ipsilateral (red) and (blue) contralateral mastoid sites. Only the 3 kHz threshold of the ipsilateral side was significantly lower than the contralateral side ( $p < 0.05$ ).



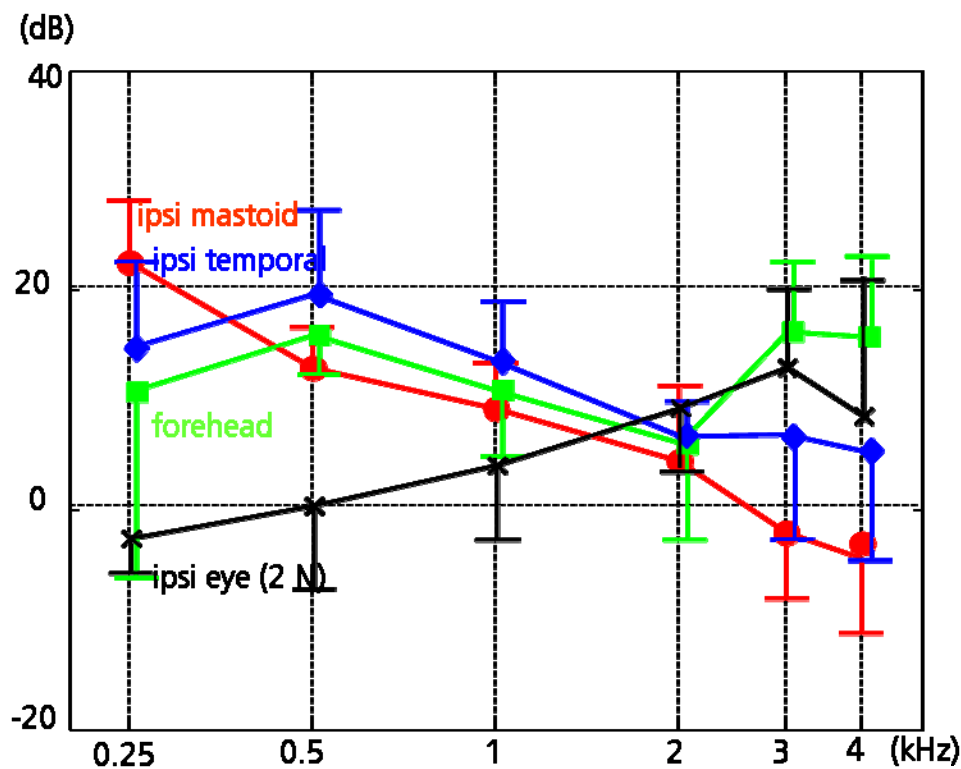
**Fig. 9.** Mean BC thresholds of subjects with single sided deafness in ipsilateral (red) and contralateral (blue) temporal region. The thresholds of the ipsilateral temporal region were significantly lower than stimulation from the contralateral temporal region at 2, 3, and 4 kHz ( $p < 0.05$ ).

## 4.2 Vibration measurements of the skull

### 4.2.1 Results of skull bone vibrations with excitation magnitude of 5 N

#### 4.2.1.1 Normal subjects

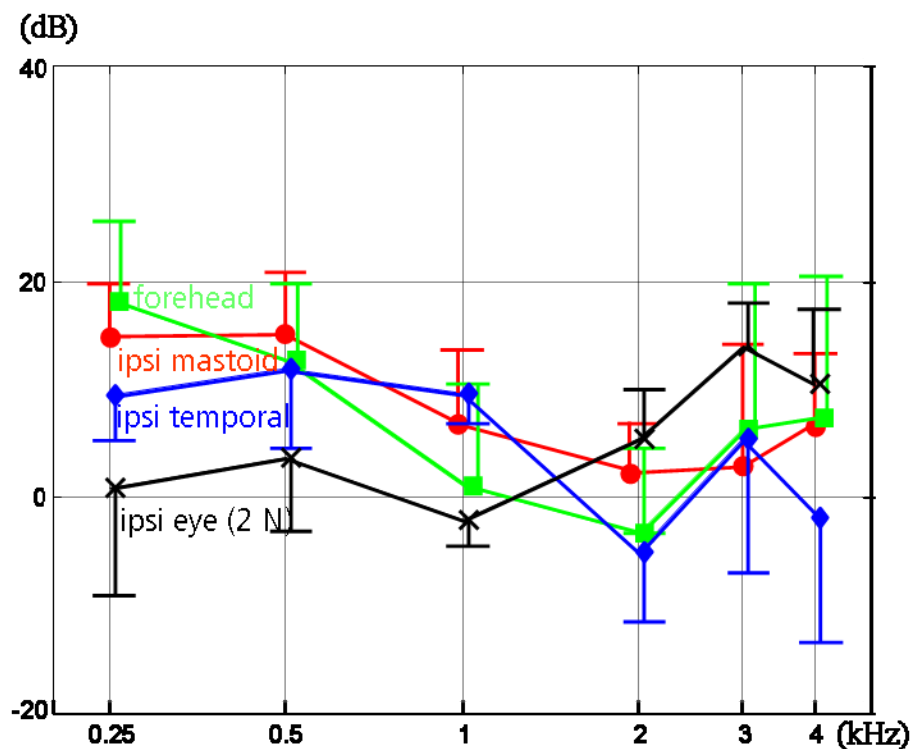
Skull vibrations of normal subjects at low frequencies were similar up to 2 kHz for all sites of stimulation except at the eye, where vibration amplitudes were significantly ( $p < 0.05$ ) smaller. In contrast to the vibrations of direct bone stimulation, skull vibrations induced by stimulation at the eye were increasing in amplitudes with higher frequencies. Vibration measurements at the teeth with frequencies of less than 2 kHz from the eye stimulation were significantly smaller than those from stimulation of the mastoid, but they were significantly bigger above 2 kHz ( $p < 0.05$ ). Vibrations from stimulation at the temporal region and the forehead site were significantly higher at 0.25, 0.5 and 1 kHz than stimulation of the eye ( $p < 0.01$ ,  $p < 0.05$ ). Skull vibrations at 0.25 kHz for stimulation of the mastoid were significantly ( $p < 0.05$ ) higher than stimulation of the forehead, but they were significantly ( $p < 0.001$ ) lower at 3 and 4 kHz (Fig. 10).



**Fig. 10.** Mean levels of skull bone vibrations of different sites in normal subjects ( $n=10$ ). Below 2 kHz, skull vibrations from ipsilateral eye stimulation were significantly smaller than those from stimulation of the mastoid, but above 2 kHz, they were significantly bigger ( $p < 0.05$ ).

#### 4.2.1.2 Subjects with single sided deafness

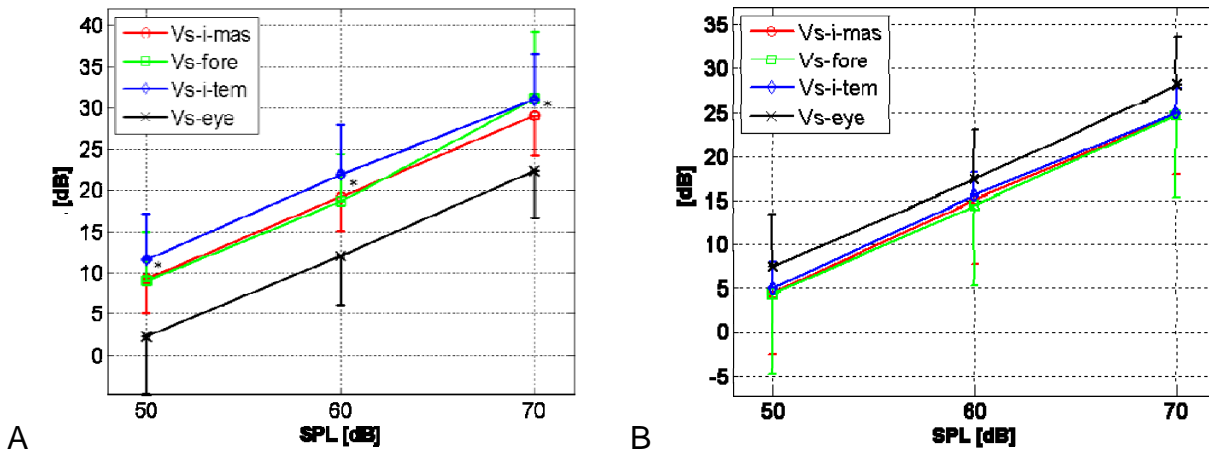
Skull vibrations of subjects with single sided deafness measured from stimulation at the eye were low at 0.25, 0.5, 1 kHz, and high at 2, 3, and 4 kHz when compared to vibrations induced by other stimulation sites. Skull vibrations from stimulation of the temporal region were lowest at 2 and 4 kHz. Skull vibrations from the ipsilateral mastoid were significantly higher than those from the eye at 0.5 and 1 kHz ( $p<0.05$ ), and vibrations from the eye were significantly lower than stimulation from the forehead at 0.25 and 0.5 kHz ( $p<0.05$ ). Skull vibrations from the temporal region at 0.5 and 1 kHz were significantly higher than vibrations from the eye, but at 2 kHz they were significantly lower than from stimulation of the eye ( $p<0.05$ , Fig. 11).



**Fig. 11.** Mean levels of skull bone vibrations in subjects with single sided deafness ( $n=5$ ). Skull vibrations from ipsilateral mastoid stimulation were significantly higher at 0.5 and 1 kHz than vibrations from the eye ( $p<0.05$ ).

#### 4.2.2 Dependence of the skull bone vibration on the sound level in normal subjects

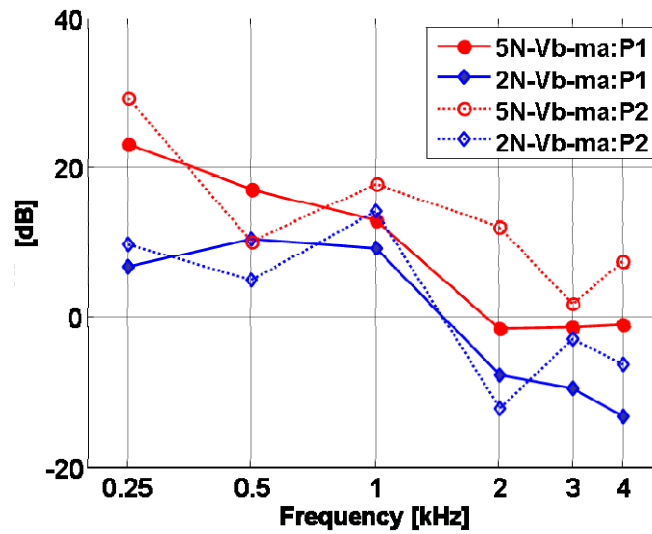
Figure 12 shows skull vibrations at 50, 60 and 70 dB of 1 kHz and 2 kHz for several sites. Skull vibrations at these sites showed similar pattern increasing linearly from 50 dB to 70 dB, except at the forehead for 70 dB. Skull vibrations from stimulation of the eye at 1 kHz were significantly lower than those from the other sites ( $p < 0.05$ , A). Skull bone vibrations for the 2 kHz stimulation of the eye were of higher levels than the other sites, but the difference was not statistically significant (B).



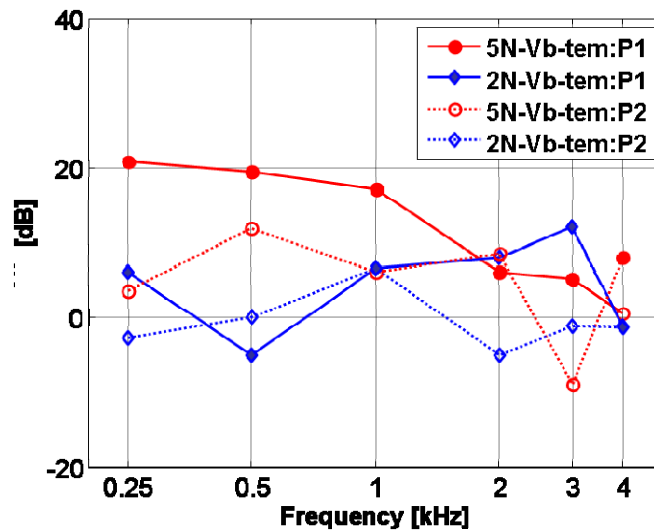
**Fig. 12.** Mean levels of skull bone vibrations of normal subjects at 50, 60 and 70dB of 1 kHz and 2 kHz. A - skull vibrations with 1 kHz, and B - skull vibrations with 2 kHz. Vs = vibrations, i-mas = ipsilateral mastoid site, fore = forehead site, i-tem = ipsilateral temporal site. At 1 kHz, skull vibrations from stimulation of the eye were significantly lower than those from the other sites ( $p < 0.05$ ), but at 2 kHz, skull bone vibrations for stimulation of the eye were of not significantly higher level than the other sites.

#### 4.2.3 Comparison between skull vibrations with headbands of 5 N and 2 N

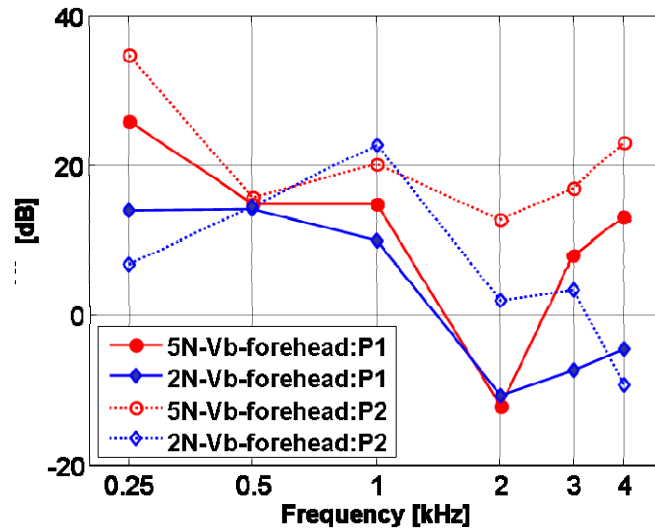
Figure 13 shows the comparison between skull vibrations induced with vibrator headbands of 5 N and 2 N at the ipsilateral mastoid site. Skull vibrations from the 5 N headband were significantly higher than from the 2 N headband at 0.25, 2, 3 and 4 kHz. Skull vibrations from the stimulation of the temporal region with 5 N were also significantly higher for frequencies below 2 kHz (Fig.14). Skull vibrations from the forehead stimulation with 5 N were significantly higher than stimulation with 2 N at 0.5, 3 and 4 kHz (Fig.15).



**Fig. 13.** Skull vibrations of two normal subjects using a 5 N (red) and 2 N (blue) headbands at the ipsilateral mastoid site. *Vb* = vibration, *ma* = mastoid site, *P1* = subject 1, *P2* = subject 2. Skull vibrations from the 5 N headband were significantly higher at 0.25, 2, 3 and 4 kHz than with 2 N force.



**Fig. 14.** Skull vibrations of two normal subjects using a 5 N (red) and 2 N (blue) headbands at the ipsilateral temporal region. *tem* = temporal site. Skull vibrations from the 5 N headband were significantly higher than with 2 N force at frequencies below 2 kHz.



**Fig. 15.** Skull vibrations of two normal subjects using a 5 N (red) and 2 N (blue) headbands at the forehead site. Skull vibrations from the 5 N headband were significantly higher than with 2 N force at 0.5, 3 and 4 kHz.

## **5. Discussion**

This thesis examined audiometric pure-tone thresholds of vibrator stimulation as used routinely in clinical audiometry for what is known as “bone-conduction” hearing. The thresholds obtained at different sites were measured and compared in normal hearing subjects and in subjects with single sided deafness. In general, results of previous work [3-4, 6] were replicated. Most sensitive thresholds were obtained at the ipsilateral temporal “ultrasound window”, a region above the zygomatic arch where the bone covering the skull contents is remarkably thin. Thresholds obtained by stimulating the soft tissue of the orbit were higher by about 20 dB, but they demonstrate that direct bone vibration is not necessary for conductive hearing induced by a vibrator. The inclusion of subjects with single sided deafness allowed in depth measurements of the transcranial attenuation. Results confirm that reliable thresholds measurements of one ear can be obtained in subjects with normal hearing if appropriate masking is applied. The transcranial attenuation is higher when the ultrasound window is used as stimulation site instead of the mastoid, particularly at higher frequencies.

As a novel addition, this thesis measured also amplitudes of skull bone vibrations which were induced by the BC vibrator at the different sites. An accelerometer was coupled to the teeth. Even though these measurements were not carried out at threshold levels, but at a stimulation level of 50 dB HL, they were shown to be highly linear. Thus, they can be related to the threshold measurements. Different patterns of induced vibrations were found for direct bone stimulation sites and the soft tissue stimulation site. While direct bone stimulation induced the highest amplitude of bone vibrations at low frequencies, soft tissue stimulation did so at high frequencies. Indeed, these high frequency vibrations were as high as or even higher than those of the direct bone vibrations at lower frequencies.

Sounds are transmitted to the cochlea in two ways: airborne sound and impact sound. The measurement of impact sound by subjective thresholds with a vibrator in contact to the head is a technique which has been around for a long time. It provides information about the sensitivity of the cochlea independent of physiological air conduction of sounds. Even though different mechanisms of impact sound transmission are recognized, they have been assumed to consist primarily or even exclusively of bone vibrations [7, 24, 45]. Different sensitivity at different sites of stimulation has also been recognized since a long time. Richter and Brinkmann [36] described a difference of more than 11 dB for BC thresholds sensitivity in the frequency range of 0.25 – 8 kHz between a forehead and a

mastoid site. Stenfelt and Goode [37] measured about the same difference in cadaver skull bone. Our results are similar to these findings. While the dynamic range of impact sound measurements is clearly better at the mastoid site in comparison to the forehead site, more constant and repeatable placement of the vibrator is possible at the forehead site leading to better clinical repeatability and reliability of threshold measurements.

Sohmer et al. [2] described the use of the temporal region above the zygomatic arch, the ultrasound window to the skull contents, as stimulation site for impact sound transmission. They found significantly better BC audiometric thresholds at this site than at the forehead, concluding that the thin skull bone at the temporal region helps to transmit sound waves to the skull contents.

Taken our results of normal subjects and subjects with SDD together, the sensitivity was found at the temporal site to be as good as or even better than at the mastoid site (Fig. 1, 2). Moreover, the vibrator can be placed as reliable as at the forehead site. Thus, the temporal site should be evaluated further as an alternative to the standard clinical use of the mastoid. Our additional finding of more transcranial attenuation at the temporal site compared to the mastoid (Fig. 6-9) also supports this conclusion because more attenuation means more tolerance for correct masking, another possible advantage in every day clinical audiometry.

Sohmer et al. [2] were also the first to demonstrate clearly that impact sound can be transmitted to the inner ear without actual bone vibration. This thesis replicates their threshold measurements by using the same stimulation site of the soft tissue content of the orbit including the eye ball. In addition, we used a standardized pressure of 2 N. The recommended pressure of 4 N or more for clinically used sites cannot be applied to the eye because of discomfort and possible damage to the eye, but 2 N was supported well by all of our subjects. Thresholds were significantly higher by 10-20 dB (Fig. 1, 2).

In contrast to the ultrasound window site of stimulation, there is little if any clinical application of using the orbit as stimulation site. The interest of this site lies in the transmission of sound to the inner ear by soft tissue excluding bone. The orbit contains the eye and other soft tissues which are connected to the skull contents through fissures and foramina. Thus, it is likely that vibrations induced in the eye are transmitted through these communication routes to the skull contents and the cochlea [3]. The exact pathway of sound transmission to the inner ear through the skull contents is not clear. Sound may



reach the inner ear partially through natural fluid connections between the cerebrospinal fluid and the perilymph such as the aquaeducti or the internal acoustic meatus.

A local perturbation of the perilymph such as may constitute an effective stimulus in stapes movements can be excluded, just as much as in transmission by actual bone vibrations. The question remains how much actual bone vibrations can be induced by the soft tissue sound waves leading to inner ear stimulation by an indirect osseous pathway. This thesis measured objectively bone vibrations to answer this question partially.

Ideally, bone vibrations should be measured near or at the otic capsule to gain definitive information. Obviously, such measurements are not possible with human subjects.

Measurements close to this site may be possible using the osseo-integrated fixture in patients fitted with BAHA, but our subjects including those with SSD were not fitted with BAHA. Therefore, we used an accelerometer coupled to the teeth for measurements of bone vibrations. Teeth are known to be a good site for BC stimulation and the absence of any soft tissue damping makes this site more sensitive than any transcutaneous measurements. Moreover, Stenfelt and Hakansson [42] measured bone-conducted sound at three positions: percutaneous titanium implants in the temporal bone (BAHA), the mastoid and the teeth. Using the mechanical impedance of the teeth, the parameters for the vibration transmission through the teeth was calculated. Stenfelt and Hakansson showed that for reliable assessment of a BAHA, the teeth are preferable to the mastoid as excitation site. Bone-conduction audiometry might also be considered with the teeth as the excitation point. Dahlin et al. [43] found in their investigation that the teeth are more reliable than the mastoid because the sensitivity of a tooth does not change from point to point on its surface. Finally, it was found that the teeth can be used for the application of bone-conducted sound, in particular for pre-operative assessment of a BAHA in a patient and quality control of hearing device.

Nevertheless, the distance between the inner ear and the teeth will introduce unpredictable effects if vibrations measured at the teeth are compared to threshold measurements. Von Békésy [12] described that global skull vibrations and standing travelling waves were induced by the application of a bone vibrator on the skull. Sohmer et al. [2] showed that the magnitude of bone vibrations clearly declined with distance from the bone vibrator by the order of at least 15 dB. The decline of vibration magnitude according to the distance from the bone vibrator was also reported by Dunlap et al. [27] and Stenfelt et al. [35] for dried skulls, as well as by Durrant and Hyre [40] in normal subjects. They

reported that the magnitude of vibration stimulation diminished along the distance of the transmission pathway [41].

Keeping in mind these limitations, our findings of bone vibration measurements still provide interesting results. The pattern of induced vibrations for the eye site was clearly different from that for other stimulation sites, where the vibrator was placed over bone (Fig. 10, 11). Eye stimulation induced lower bone vibrations than the other sites below 2 kHz, but just as high or higher above 2 kHz. Skull-bone vibrations decreased with increasing frequency for mastoid and temple stimulation. Stimulation of soft tissue, presumably including skull contents, induced primarily high frequency skull vibrations. The different patterns of bone vibrations as measured at the teeth contrast with the similar patterns of thresholds at different sites (Fig. 1, 2). Because thresholds are highest at high frequencies also for the eye site, it can be concluded that bone vibrations contribute little to threshold sensitivity, at least in low frequencies. Moreover and assuming that the temporal stimulation site induces more skull content vibrations than the mastoid site, the significantly higher transcranial attenuation at high than at low frequencies (Fig. 6-9) fit well with this notion. The finding of relatively large attenuation at the temporal region particularly at frequencies of 2 kHz and higher may point to a more prominent portion of sound conduction by the skull contents rather than by real bone conduction for the temporal in comparison to the mastoid stimulation. A more prominent non-osseous conduction can be expected to be less effective at higher frequencies and transcranial attenuation to be higher. This fits well with the flatter curves of the ipsilateral side (Fig 6 and 9).

The examination of subjects with single sided deafness allowed for reliable testing of transcranial attenuation without concerns about adequate masking. It confirmed the findings in normal hearing subjects. The survey indicated that in general BC hearing thresholds of normal hearing subjects and subjects with single sided deafness showed the same patterns (Figs. 1 and 2), but averaged BC thresholds from the contralateral temporal region were significantly different at 0.25 kHz ( $p < 0.01$ , Fig. 3). The better BC hearing thresholds at low frequencies were due to the occlusion effect [31] created by insert earphones in the external auditory canal. The occlusion was accepted to prevent the AC transmission of sound radiated by the vibrator. Several researchers showed that BC hearing thresholds for the occluded ear canal are significantly lower than those obtained with an open ear canal at frequencies below 1 kHz [34, 35].

## **Conclusions**

Our combined findings of higher transcranial attenuation at the temporal site than at the mastoid site for high frequencies and of less objective bone vibrations as measured at the teeth from the eye stimulation site for low frequencies supports the possibility of a direct stimulation of the inner ear through a soft tissue pathway without significant contribution of indirect bone vibrations. However, precise quantification of the contribution of the two pathways of impact sound to the inner ear, bone vibration and sound waves through the soft tissue and fluid skull contents, is not possible with our measurements. Our results indicate that more soft tissue and fluid contributions are involved at the temporal stimulation site compared to the mastoid site. The use of the temporal stimulation site at the ultrasound window can be considered as routine placement of the vibrator for clinical BC testing. It offers both sensitive thresholds and reliable placement of the vibrator, beside the advantage of less transcranial attenuation.

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## **8. Curriculum vitae**